Vulnerability Evaluation Framework Review [1]

Background

In 2008, the U.S. Environmental Protection Agency (EPA) published the "Vulnerability Evaluation Framework" (VEF) identifying factors that should be considered in the geologic sequestration of carbon dioxide (CO_2).[2] As stated in the VEF document, it is not official EPA regulatory guidance, but is designed to frame site specific considerations that may require more in-depth evaluation at a geologic sequestration project. The VEF is useful in helping identify conditions that could increase the potential for adverse impacts to occur from commercial-scale geologic sequestration of carbon dioxide.

As stated in the VEF, attempting to quantify risks potentially associated with geologic sequestration will become more feasible as information is collected from pilot- and commercial-scale projects. The Northern California CO_2 Reduction Project (NCCRP) is a small-volume injection project with the objective of demonstrating the safety and feasibility of CO_2 storage in saline formations in the northern region of California's Central Valley. The project will yield data and information that will be informative to future analyses of risk. As such, many of the components identified in the VEF for commercial-scale projects do not apply or are of marginal applicability to the small-scale NCCRP.

The VEF identifies three components that could increase vulnerability to adverse impacts of a sequestration project. These include

- ✓ Geologic sequestration system and geologic attributes,
- ✓ Spatial area of evaluation, and
- ✓ Potential impact categories and receptors.

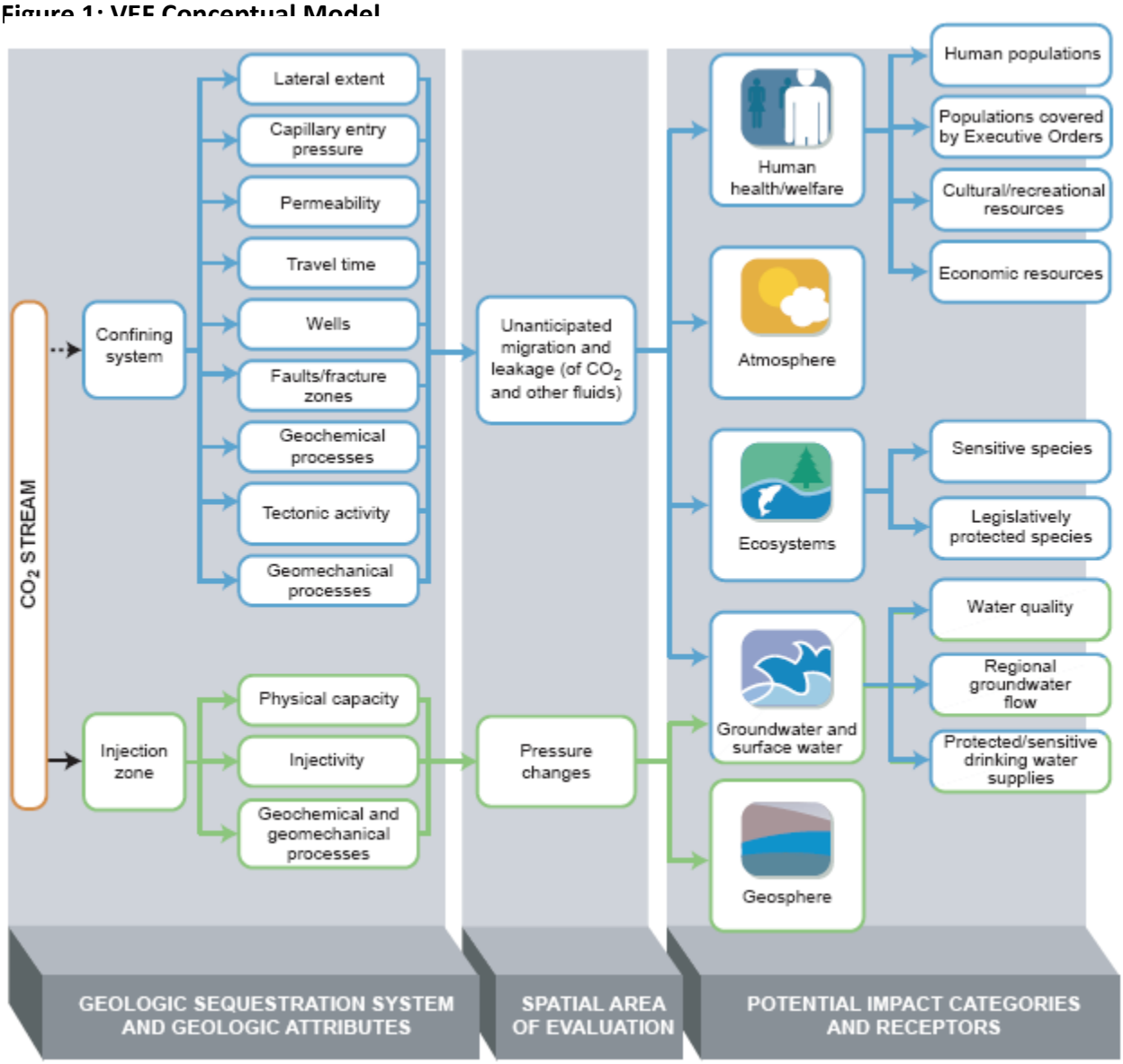
Figure 1 VEF Conceptual Model, is from the VEF document and shows the overall relationship among potential subcomponents of a sequestration project.

Many of the considerations identified in the VEF are addressed for the NCCRP in a Class V Underground Injection Control Permit Application (UIC Permit Application) submitted to the EPA or in an Initial Study submitted to Solano County in support of a Conditional Use Permit (CUP). Copies of both the UIC Permit Application and the Initial Study are available at the Solano County Department of Resource Management. Most topics identified in the VEF are discussed here briefly. Where germane, references are made to the UIC Permit Application and the Initial Study.

[1] Prepared by Fritts Golden, Senior Associate, and Emily Capello, Associate, Aspen Environmental Group, from information in the referenced Initial Study, UIC Permit Application, and Potential Induced Seismicity Report. June 2010.

[2] *Vulnerability Evaluation Framework for Geologic Sequestration of Carbon Dioxide*. USEPA. July 10, 2008. EPA430-R-08-009. Available at http://www.epa.gov/climatechange/emissions/downloads/VEF-Technical_Document_072408.pdf

Figure 1: VEF Conceptual Model



Source: *Vulnerability Evaluation Framework for Geologic Sequestration of Carbon Dioxide,* July 10, 2008, USEPA, EPA430-R-08-009, Figure 3.1, page 13

1. Geologic Sequestration System and Geologic Attributes

The VEF characterizes the geologic sequestration system in terms of (a) the CO_2 stream that is to be held within (b) an underground confining system and introduced into (c) the injection zone.

(a) CARBON DIOXIDE STREAM. When a CO_2 stream is captured at an industrial source, it may have various impurities entrained in it. The effects of these impurities need to be considered

Relationship to Project: The NCCRP would use a commercial or better grade (e.g., food-grade) of CO_2 from a commercial supplier in the region. This would be delivered to the site by tanker trucks

during the injection part of the project. Because of the quality of the CO_2, potential adverse impacts from impurities in the CO_2 would not be expected.

- *For additional details regarding the CO_2 see Section 1.9 (CO_2 Storage Tanks) of the Initial Study.*

CO_2 can be considered a hazardous material because of its irritant and asphyxiant characteristics. It is heavier than air and tends to sink to low elevations, displacing air. After analysis, all potential impacts of the small-volume injection project are found to be less than significant with proposed mitigation. Additionally, C6 Resources will install a CO_2 monitoring system at selected locations on the pad and/or provide individual personal monitoring devices to warn site workers of high CO_2 levels. They will also be instructed in leaving the site and assembling at a higher elevation nearby.

- *CO_2 hazards are addressed in Section 3.7 (Hazards and Hazardous Materials) of the Initial Study.*

(b) CONFINING SYSTEM. The confining system for CO_2 is the geologic formation, or group of formations, composed of impermeable or less permeable material overlaying the injection zone. The confining system acts as a barrier to the upward flow of fluids. A variety of geologic attributes influence the potential for unanticipated migration and leakage past the confining system, including lateral extent, capillary entry pressure, permeability, travel time, wells and other artificial penetrations, faults/fracture zones/tectonic activity, and geochemical and geomechanical processes. The VEF approach for considering the confining system includes:

Establish presence of confining system over necessary lateral extent.

Relationship to Project: As the NCCRP is a small-volume project, the lateral extent of the confining system is significantly greater than the geologic sequestration footprint, which would only extend over a radius of about 350 feet from the point of injection into the sandstone formation. There are five potential "pairs" of sandstone/shale strata that form multiple, stacked confining interval/injection interval combinations beneath the test site. The potential major injection interval sandstones are separated by thick shales of marine origin, which will provide the laterally extensive seals for the pilot. Additionally, the objectives of the project are to appraise and establish the presence of confining shales and permeable injection interval sandstones beneath the Montezuma Hills synclinal structure (within the Sacramento basin). Prior to authorizing CO_2 injection, the EPA would evaluate the geologic and geophysical data obtained during well drilling.

- *Additional information is found in Section G.1 (Injection and Confining Zones) of the UIC Permit Application.*

Capillary entry pressure. The capillary entry pressure is defined in the VEF as the added pressure that is needed across the interface of two immiscible (non-mixing) fluid phases (e.g., supercritical CO_2 and brine) in order for CO_2 to enter the confining system. Elevated vulnerability may be associated with exceedance of the confining system capillary entry pressure.

Relationship to Project: Drilling and testing the wells will confirm the stratigraphy beneath the injection site, including characterizing the geologic material and the thickness of each formation. The capillary entry pressure for the NCCRP will be regulated by the UIC permit issued by EPA; it will be determined by EPA after the agency evaluates data collected during development of the

wells. The project may include cased-hole testing to further characterize the injection interval sandstones

- *For additional information see Section I.2 (Cased-Hole Testing Program) of the UIC Permit Application.*

Permeability. Permeability refers to the ability of a geologic material to allow transmission of fluid through pore spaces within the rock. Elevated vulnerability may be associated with geologic materials with a high permeability, one greater than clay, shale, or siltstone.

Relationship to Project: Five potential "pairs" of strata form the confining interval /injection interval (i.e., shale/sandstone) combinations. They are, in stratigraphic order, shallowest to deepest:

- Nortonville Shale/Domengine Sandstone
- Capay Shale/Hamilton Sandstone
- Meganos Shale/Anderson Sandstone
- Anderson Shale/ Upper Martinez Sandstone
- Martinez Shale/Martinez123 Sandstone

- *For additional information see Section G.1 (Injection and Confining Zones) and Attachment G (Geologic Data on Injection and Confining Zones) of the UIC Permit Application.*

Travel time. Travel time refers to the interval of time that is required for a fluid (e.g., CO_2 or brine) to migrate across the thickness of the confining system. Travel times that compromise the integrity of the project are considered to result in elevated vulnerability.

Relationship to Project: Computer modeling of CO_2 migration has been performed. However, the project is a pilot project and the objectives of the project are to appraise and establish the presence of confining shales and permeable injection interval sandstones beneath the Montezuma Hills synclinal structure (Sacramento basin). Additional data collected during well drilling will be used to refine models and to better understand the confining systems, including travel time.

- *UIC Application Section N.4 (Estimation of Pilot Injection Duration) and Section N.5 (Plume movement) discusses the modeling performed for the pilot injection.*

Evaluate integrity of the confining system.

Wells. Wells (and other artificial penetrations such as boreholes) may serve as conduits for fluid movement and hence could result in elevated vulnerability to adverse impacts.

Relationship to Project: No recorded wells penetrate the Confining Zone or the Injection Zone in the vicinity of the project. This eliminates known potential artificial migration pathways to the surface or between formations. (See Attachment B Maps of Well/Area and Area of Review from the UIC Permit Application).

Given the relatively small quantity of CO_2 that would be injected and the limitations on capillary entry pressure stipulated in the UIC permit, it is highly unlikely that the CO_2 would migrate or the project would compromise the integrity of the geology or result in elevated vulnerability.

Faults/fracture zones. Faults are breaks in the Earth's crust that occur when the crustal rock is either compressed or pulled apart, and slippage has occurred across the break. A fracture is any

local separation or discontinuity plane in a geologic formation that divides the rock into two or more pieces, but no slippage has occurred.

Relationship to Project. The seismicity of the San Francisco Bay area is concentrated along transverse faults associated with movement of the Pacific Oceanic plate in a northward direction relative to the North American continental crustal plate. More than ninety percent of the seismic events located within the project vicinity are deeper than 8 miles (13 kilometers), well below the formations of interest for the pilot test.

- *Seismic history of the project vicinity and the region are discussed in the UIC Permit Application, see Section F.1.3 (Seismicity).*

Geochemical processes. Geochemical processes are chemical reactions that may cause alterations in mineral phases. Mineralogy and pH (scale of acidity-alkalinity)that favor the formation of conduits in the confining system, by dissolution and/or decreasing molar volume, increase vulnerability; those chemical reactions that do not favor the formation of conduits through dissolution and/or increases in molar volume decrease vulnerability.

Relationship to Project. Fluid samples will be recovered from each of the major sand intervals. These will be used to determine formation fluid characteristics. A number of tests will be run on the samples including mineral composition and pH.

- *See Section I.1.4 (Open-hole Well Logging Program) of the UIC Permit Application.*

Tectonic activity. Tectonically active settings may be more likely to have faults and/or fractures that may be provide pathways for migration of CO_2. Areas with seismic hazard ratings that indicate the potential for seismicity to cause adverse impacts are considered to have elevated vulnerability.

Relationship to Project. The seismicity of the San Francisco Bay area is concentrated along transverse faults associated with movement of the Pacific Oceanic plate in a northward direction relative to the North American continental crustal plate. Ninety percent of the seismic events located within the project vicinity are deeper than 8 miles (13 kilometers), well below the formations of interest for the pilot test.

- *Seismic history of the project vicinity and the region are discussed in the UIC Permit Application, see Section F.1.3 (Seismicity).*

Geomechanical processes. These are processes that may alter the structural integrity of geologic material. Appropriate evaluation metrics for this attribute include fracture pressure, fracture/fault reactivation pressure, and orientation of the fracture or fault relative to the orientation of the principal regional stress regime. If the fracture pressure and the fracture/fault reactivation pressure (multiplied by a safety factor) are exceeded, vulnerability is considered to be elevated. It should be noted that geomechanical processes occur at a continuum of scales. For example, potential impacts such as deformation of geologic formations can occur without necessarily adversely affecting the integrity of the confining system.

Relationship to Project. Mini-frac injection tests will be used to estimate the fracture closure pressure of the formation. The tests will provide the in-situ minimum stress that will define a maximum bottomhole pressure for injection tests for reservoir characterization and for CO_2 injection.

- *See UIC application Section I.2.2.1 (Mini-frac Injection Tests) for discussion of the use of the mini-frac injection tests to estimate the fracture closure pressure of the formation.*

(c) INJECTION ZONE. The injection zone is a geologic formation of sufficient areal extent, thickness, porosity, and permeability to accommodate the CO_2 injection volume and injection rate. This zone is characterized by its physical capacity, injectivity, and geochemical and geomechanical processes.

Physical capacity.

Relationship to Project: The Central Valley saline formations are estimated to have storage capacity of 50 to 200 gigatonnes of CO_2. This project would inject up to 6,000 tonnes (i.e., 0.000006 gigatonnes) of CO_2. This is a very small volume in relation to the target formation. One of the major objectives of the project is to demonstrate and evaluate the safety and feasibility of CO_2 storage in saline formations in the northern region of California's Central Valley.

- *See UIC application Section 1.8 (Project Benefits and Objectives)*

Injectivity.

Relationship to Project: The injectivity of the geologic formation is unknown at this time. During the injection process, it is planned that as much as approximately 300 hundred tons of CO_2 per day would be introduced into the formation; however, the actual rate will depend on formation characteristics and may be much lower. The operational factors of the injection will be reviewed and revised as well data and baseline data become available.

- *Section N.3 (Injection Prediction) of the UIC Permit Application includes information regarding the simulation models which predict the maximum injection rate profile over time.*

Geochemical and geomechanical processes.

Relationship to Project: Geochemical modeling for the injection of CO_2 into brine indicates that the pH in the formation brine should not drop below a value of about pH 5.3, due to the buffering provided by naturally occurring reactive minerals in subsurface formations.

- *See Attachment P (Monitoring Program) of the UIC Permit Application.*

2. Spatial Area of Evaluation: Geologic Sequestration Footprint

The geologic sequestration footprint is based on the size and shape of the CO_2 subsurface plume and the pressure front associated with the plume.

Relationship to Project: The NCCRP is a small-volume injection project. The edge of the plume is expected to have a radius of about 350 of feet from the point of injection, which is over 2 miles below the surface. The plume size (sequestration footprint) is not significant given (1) it is in the range of a few hundred feet away from the point of injection, (2) the likely permeability in the injection interval and (3) the limited injected volume (less than 6,000 tonnes). Well injectivity is largely unknown for the time being, due to uncertainties on injection interval properties (porosity, permeability, relative permeability, rock compressibility, fracture pressure, etc.) and well completion quality (well skin). This injection prediction work is therefore focused on identifying the possible injection rate potentials in a few subsurface scenarios, which bound expected conditions. This is true for the plume movement as well.

- *See Section N.5 (Plume Movement) of the UIC application, which addresses modeling of the CO_2 plume.*

3. Potential Impact Categories and Receptors.

Unanticipated CO_2 migration or leakage, or changes in subsurface pressure, could potentially cause adverse impacts to human health and welfare, the atmosphere, ecosystems, groundwater and surface water, or the geosphere. As the project is a small-volume project, adverse impacts are not expected to occur.

- *See Initial Study in general*.

Potential Human Health and Welfare. The VEF states that the vulnerability of a population to the release of CO_2 is affected by the population's size and sensitivity to CO_2 and the proximity to and concentration of the release. Potential receptors are human populations (including populations covered by Executive Orders), cultural and recreational resources, and economic resources.

Relationship to Project: As stated in the Initial Study, the nearest sensitive receptor is one mile away from the injection site. No impacts to any sensitive receptors, including populations covered by Executive Orders (environmental justice populations), would occur.

The nearest known cultural resource is located 0.75 miles from the project site. The nearest recreational resource is located approximately 2.3 miles from the project site. No impacts to cultural resources or recreational resources are expected.

The CO injection is not expected to preclude existing land use or subsurface activities at the site.

- *See Initial Study in general*. *In particular see Section 3.5, (Cultural Resources), Section 3.14, (Recreation), and Section 3.9 (Land Use and Planning).*

Potential Atmospheric Impacts. As the VEF states, releases of CO_2 from the geologic sequestration could reduce the benefits of capturing CO_2.

Relationship to Project: The project is a small-volume project to demonstrate the safety and feasibility of CO_2 storage in saline formations in the northern region of California's Central Valley. Significant releases of CO_2 are not expected. Some releases will occur when equipment is purged or during transfer of CO_2 from delivery tankers to storage tanks

- *See the Project Description in the Initial Study. Air quality impacts are discussed in Section 3.3 of the Initial Study.*

Potential Ecosystem Impacts. Potential effects could impact sensitive species and legislatively protected species.

Relationship to Project: An environmental review of impacts to sensitive species and legislatively protected species concludes that all impacts would be less than significant. These species are not present on the site. Potential impacts of the project on deep geologic ecosystems are unknown.

- *See Initial Study Section 3.4 (Biological Resources).*

Potential Groundwater and Surface Water Impacts. Potential effects could impact water quality, regional groundwater flow, and protected/sensitive drinking water supplies.

Relationship to Project: The CO_2 injection would occur at nearly 2 miles below potable water aquifers in the area and would be separated by several thick impervious shale formations. Any re-injection of produced brine into the storage formations would not affect potable ground-water quality. Migration of CO_2 to groundwater aquifers is unlikely, given the small volume of CO_2, the depth of the injection, the multiple casings and cement of the well bores, and the multiple thick shale formations separating the injection zone from aquifers. However, at the request of Solano County, well water will be sampled and tested to determine if there is a change. There is no surface water near the site, but appropriate best management practices applicable to the project would be incorporated in the project to minimize any potential impacts to surface water.

- *See Section 3.8 (Hydrology and Water Quality), in the Initial Study and Attachment D, Maps and Cross Sections of Underground Source of Drinking Water of the UIC Permit Application.*

Potential Geosphere Impacts. As stated in the VEF, changes in subsurface pressure from geologic sequestration could potential cause fracturing or reopening of faults and fracture zones.

Relationship to Project: Pressure in the geologic formations at 2 miles deep is on the order of 5,000 pounds per square inch (psi). Modeling indicates that at 1.8 miles from the injection well, the CO2 injection temporarily will add approximately 11 psi, an extremely small increase. In addition, the nearest fault is approximately 3 miles from the injection site, and the added pressure at that distance is expected to be even less.

- *Potential impacts related to seismic activities are addressed in the Initial Study (Section 3.6 Geology and Soils). See also a report on potential induced seismicity report:* Draft Preliminary Report on the Potential for Induced Seismicity Related to CO2 Injection, Montezuma Hills Pilot Test, Solano County*, CA, prepared by Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory.*

Mitigation and Monitoring

Relationship to Project: Because the CO_2 volume to be injected is small, the site is remote from sensitive receptors, and the injection point is over 2 miles deep, the NCCRP results in low vulnerability. Adverse impacts are not expected.

Monitoring will be a key aspect of the project. Data would be collected on how CO_2 behaves within the formation and on the nature of the geology and its characteristics. Baseline data collection would be performed to evaluate the composition, physical properties, pressure and temperature of native fluids found in the saline formation and near-surface groundwater. Baseline measurements would be compared to data collected during and after CO_2 injection to look for changes in geochemistry, hydrochemistry, and fluid pressures, indicating potential leakage from the target injection formation into overlying formations. Monitoring would be on-going during and after the injection and a post-injection geophysics evaluation will be performed.

- *Attachment P Monitoring Program of the UIC Permit Application provides additional monitoring details.*